Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2023

Passive Frequency Control Characteristics of $S\text{-}CO_2$ Direct-Cycle Micro Modular Reactor

Seongmin Son [ab]*, Jeong Yeol Baek[c]
[a]*Department of Smart Plant Engineering, Kyungpook National University*
[b]*Department of Convergence & Fusion System Engineering, Kyungpook National University*
[a&b]*2559, Kyungsangdae-ro, Sangju-si, Gyeongsangbook-do, Korea*
[c]*Dept. Nuclear & Quantum Eng., KAIST, 291 Daehak-ro, Yuseong-Gu, Daejeon 34141, Republic of Korea*
**Corresponding author: seongminson@knu.ac.kr*

1. Introduction

Supercritical fluids also exhibit high compression efficiency near the critical point. Fluids close to the critical point can compress higher pressure carbon dioxide with relatively little energy, similar to pumping a liquid. Power generation systems that utilize this property to perform compression near the critical point are known as supercritical CO_2 power generation systems [1]. These systems achieve high efficiency by reducing the energy required for compression and operate at a higher minimum pressure point than other power systems, resulting in a lower compression ratio. This, in turn, reduces the size of the turbomachinery, thereby decreasing the site footprint. Due to these advantages, supercritical CO_2 power generation systems are gaining attention from both academia and industry as a innovative technology, especially for future Small Modular Reactor (SMR) applications [1].

Since CO_2 is also a candidate core coolant for gas-cooled reactors, direct-cycle $S\text{-}CO_2$ systems are also under consideration, where the $S\text{-}CO_2$ system is connected directly to the reactor core. This is one of the more attractive options for small or micro modular reactors. The KAIST-MMR is one such attempt, which is a direct-heating reactor that uses $S\text{-}CO_2$. For a reactor with such a small capacity, the amount of nuclear fuel is expected to be small even during long-term operation, and the direct-cycle design shows promise in avoiding excessive radiation exposure for maintenance workers [2].

Another performance expectation for small reactors is load-following. In general, small reactors are expected to have superior load-following performance compared to large reactors, but more research is still needed on the load-following capability of $S\text{-}CO_2$ direct-cycle reactors. In particular, little research has been conducted to date to determine load-following performance from a sharp frequency control perspective.

This study analyzes the behavior of a micro-modular reactor under abrupt frequency control using the KAIST-MMR as an example. It aims to determine whether passive reactor control is possible and provides an analytical analysis of the reactor's behavior.

2. Methodology

This study employs the six-group point kinetics and reactivity feedback coefficients presented in Table 1 and Table 2, which are based on previous studies [3,4]. The reactivity feedback coefficient is dependent on the fuel temperature and working fluid density.

Table 1. Coefficients for point kinetics

Energy group	Beta value (β_i)	Lambda value (λ_i)
1st	1.86E-04	1.34E-02
2nd	1.09E-03	3.24E-02
3rd	1.19E-03	1.22E-01
4th	2.77E-03	3.10E-01
5th	1.39E-03	8.74E-01
6th	6.04E-04	2.94E+00
Effective	7.10E-03	5.53E-01

Table 2. Core general information

Design Parameter	Value
Fuel Temperature Coefficient	-0.366 pcm/K
Coolant Density Coefficient	2.063 pcm/(kg/m^3)

Table 3 provides a summary of the general cycle information of the KAIST-MMR. The layout of the KAIST-MMR is a simple recuperated S-CO2 cycle, and the entire model is calculated using the DNN-modified GAMMA+ code [5, 6].

Table 3. Cycle information of KAIST-MMR

Parameter	Value
Maximum Temperature (Turbine Inlet)	823.15 K
Maximum Pressure (Compressor Outlet)	20 MPa
Turbine Efficiency	92 %
Minimum Temperature (Compressor Inlet)	333.15 K
Minimum Pressure (Compressor Inlet)	8 MPa
Compressor Efficiency	85 %
Turbomachinery RPM	19300
Recuperator Effectiveness	92 %
System mass flow rate	180 kg/s
Reactor Power	36.4 MW_{th}
Cycle Efficiency	34 %

3. Results and Discussion

The analysis was conducted for a rapid frequency control scenario involving two selected scenarios: a 30% external electricity load drop in 30 seconds (100% to

70%) and a 30% electricity output raise in 30 seconds (70% to 100%). It should be noted that these scenarios provide a conservative estimate for a typical gas turbine system. Figure 1 illustrates the electrical output of the system under these conditions. As shown in the figure, no control issues were observed in the load drop scenario, but an overshooting phenomenon occurred in the output raise scenario.

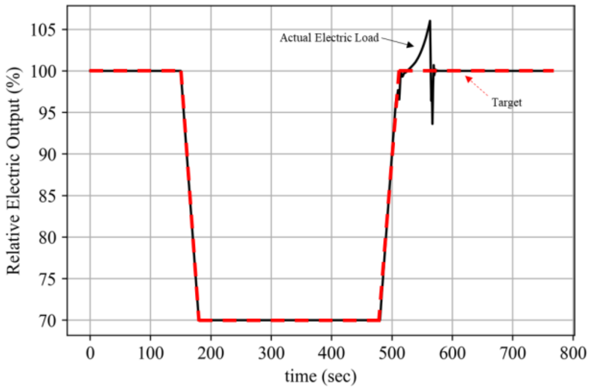

Figure 1. Reactor electric output during sudden drop and sudden raise scenario

During this period, fuel average temperature and coolant density changes as Figure 2-3.

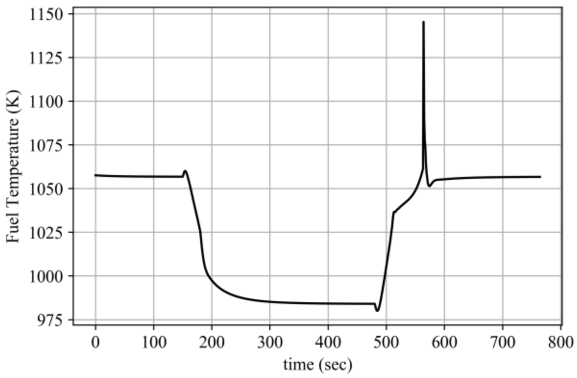

Figure 2. Fuel temperature changes throughout the frequency control scenarios

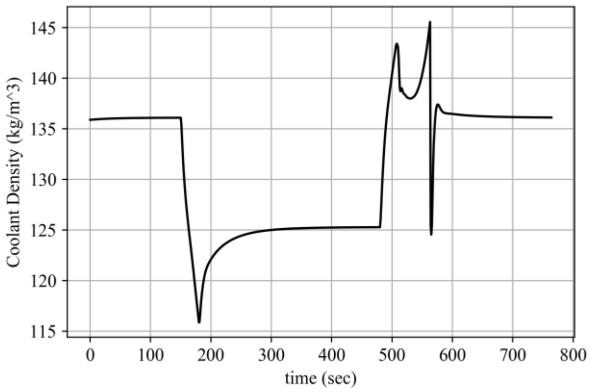

Figure 3. Coolant density changes throughout the frequency control scenarios

The resulting reactor reactivity changes are illustrated in Figure 4, which demonstrates that the reactor output can be passively controlled without any external intervention in this scenario.

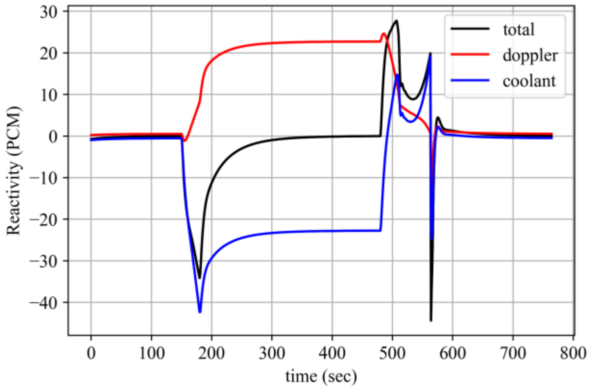

Figure 4. Core reactivity changes throughout the frequency control scenarios

In conclusion, this study has demonstrated that it is possible to passively adjust the core power without external intervention in the aforementioned scenario. Unlike a typical light water reactor, the removal or addition of system flow via inventory control has a greater impact on the coolant density than on the coolant temperature. The core output is controlled by feedback from the fluid pressure (density) in the core.

REFERENCE

[1] Dostal, V., Driscoll, M. J., Hejzlar, P., & Todreas, N. E. (2002, April). A supercritical CO_2 gas turbine power cycle for next-generation nuclear reactors. In *10th International Conference on Nuclear Engineering* (pp. 567-574). American Society of Mechanical Engineers Digital Collection.

[2] Son, S., Kwon, J., Oh, B. S., Cho, S. K., & Lee, J. I. (2020). Radionuclide transport in a long-term operation supercritical CO_2-cooled direct-cycle small nuclear reactor. *International Journal of Energy Research*, *44*(5), 3905-3921.

[3] Oh, B. S., Ahn, Y. H., Yu, H., Moon, J., Kim, S. G., Cho, S. K., ... & Lee, J. I. (2017). Safety evaluation of supercritical CO_2 cooled micro modular reactor. *Annals of Nuclear Energy*, *110*, 1202-1216.

[4] Yu, H., Hartanto, D., Moon, J., & Kim, Y. (2015). A conceptual study of a supercritical CO2-cooled Micro Modular Reactor. *Energies*, *8*(12), 13938-13952.

[5] Lim, H. S., & No, H. C. (2006). GAMMA multidimensional multicomponent mixture analysis to predict air ingress phenomena in an HTGR. *Nuclear science and engineering*, *152*(1), 87-97.

[6] Son, S., Baek, J. Y., Jeong, Y., & Lee, J. I. (2020). Impact of turbomachinery degradation on performance and dynamic behavior of supercritical CO_2 cycle. *Journal of Engineering for Gas Turbines and Power*, *142*(9).